Effects of neutrino oscillations on the supernova signal in LVD

M.Aglietta[a], P.Antonioli[b], G.Bari[b], C.Castagnoli[a], W.Fulgione[a], P.Galeotti[a], PL.Ghia[a], P.Giusti[b], E.Kemp[c], A.S.Malguin[d], G.Nurzia[e], A.Pesci[b], P.Picchi[a], I.A.Pless[f], V.G.Ryasny[d], O.G.Ryazhskaya[d], G.Sartorelli[b], M.Selvi[b], C.Vigorito[a], F.Vissani[e], L.Votano[g], V.F.Yakushev[d], G.T.Zatsepin[d], A.Zichichi[b]

[a]Institute of Cosmo-Geophysics, CNR, Torino, University of Torino and INFN-Torino, Italy

[b]University of Bologna and INFN-Bologna, Italy

[c]University of Campinas, Campinas, Brazil

[d]Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

[e]INFN-LNGS, and University of L'Aquila, Italy

[f]Massachusetts Institute of Technology, Cambridge, USA

[g]INFN-LNF, Frascati, Italy

We study the impact of neutrino oscillations on the supernova neutrino signal in the Large Volume Detector (LVD). The number of expected events for a galactic supernova ($D = 10$ kpc) is calculated, assuming neutrino masses and mixing that explain solar and atmospheric neutrino results. The possibility to detect neutrinos in different channels makes LVD sensitive to different scenarios for ν properties, such as normal or inverted ν mass hierarchy, and/or adiabatic or non adiabatic MSW resonances associated to U_{e3}. Of particular importance are the charged current (c.c.) reactions on ^{12}C: oscillations increase by almost one order of magnitude the number of events expected from this channel.

1. Introduction

In spite of the lack of a "standard" model of the gravitational collapse of a massive star, some features of its dynamics and, in particular, of the correlated neutrino emission appear to be well established. At the end of its burning phase a massive star ($M \gtrsim 8M_\odot$) explodes into a supernova (SN), originating a neutron star which cools emitting its binding energy $E_B \sim 3 \cdot 10^{53}$ erg mostly in neutrinos. The largest part of this energy, almost equipartitioned among neutrino and antineutrino species, is emitted in the cooling phase: $E_{\bar\nu_e} \sim E_{\nu_e} \sim E_{\nu_x} \sim E_B/6$ (ν_x denotes generically $\nu_\mu, \bar\nu_\mu, \nu_\tau, \bar\nu_\tau$). The energy spectra are approximatively Fermi-Dirac, but with different temperatures, since ν_e, $\bar\nu_e$ and ν_x have different couplings with the stellar matter: $T_{\nu_e} < T_{\bar\nu_e} < T_{\nu_x}$. These features are common to all existing stellar collapse models (see for instance [1–5]), and lead to rather model independent expectations for supernova neutrinos. The observable signal is then sensitive to intrinsic ν properties, as oscillation of massive neutrinos. Indeed, as we demonstrate below, oscillations change significantly the expected number of events in LVD.

The paper is organized as follows: in Sect.2 we briefly describe the LVD detector, with particular attention to the detectable neutrino reactions. In Sect.3 we recall the main features of MSW conversion [6,7] in the stellar matter, focusing on the LMA solution, favored by the most recent results on solar neutrinos. For a supernova occurring at $D = 10$ kpc, with pure Fermi-Dirac ν energy spectra, we calculate the number of events expected in LVD, in the different interactions channels. Sect.4 is devoted to conclusions and discussion of the results.

2. The LVD experiment and SN neutrino interactions

The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory, Italy, consists of

an array of 840 scintillator counters, 1.5 m^3 each. These are interleaved by streamer tubes, and arranged in a compact and modular geometry; a detailed description is in [8]. The active scintillator mass is $M = 1000$ t. There are two subsets of counters: the external ones (43%), operated at energy threshold $\mathcal{E}_h \simeq 7$ MeV, and inner ones (57%), better shielded from rock radioactivity and operated at $\mathcal{E}_h \simeq 4$ MeV. In order to tag the delayed γ pulse due to n-capture, all counters are equipped with an additional discrimination channel, set at a lower threshold, $\mathcal{E}_l \simeq 1$ MeV. Relevant features of the detector are: (i) good event localization; (ii) accurate absolute and relative timing: $\Delta t_{\rm abs} = 1\,\mu$s, $\Delta t_{\rm rel} = 12.5\,$ns; ($iii$) energy resolution: $\sigma_E/E = 0.07 + 0.23 \cdot (E/\mathrm{MeV})^{-0.5}$.

The observable neutrino reactions are:
(1) $\bar\nu_e p, e^+ n$, observed through a prompt signal from e^+ above threshold $\mathcal{E}_h$ (detectable energy $E_d \simeq E_{\bar\nu_e} - 1.8$ MeV $+2m_e c^2$), followed by the signal from the $np, d\gamma$ capture ($E_\gamma = 2.2$ MeV), above $\mathcal{E}_l$ and with a mean delay $\Delta t \simeq 180\ \mu$s.
(2) $\nu_e\, ^{12}\mathrm{C}, ^{12}\mathrm{N}\ e^-$, observed through two signals: the prompt one due to the e^- above $\mathcal{E}_h$ (detectable energy $E_d \simeq E_{\nu_e} - 17.8$ MeV) followed by the signal, above $\mathcal{E}_h$, from the β^+ decay of ^{12}N (mean life time $\tau = 15.9$ ms).
(3) $\bar\nu_e\, ^{12}\mathrm{C}, ^{12}\mathrm{B}\ \mathrm{e}^+$, observed through two signals: the prompt one due to the e^+ (detectable energy $E_d \simeq E_{\nu_e} - 13.9\,\mathrm{MeV} + 2m_e c^2$) followed by the signal from the β^- decay of ^{12}B (mean life time $\tau = 29.4$ ms). As for reaction *(2)*, the second signal is detected above the threshold $\mathcal{E}_h$.
(4) $\overset{(-)}{\nu}_\ell\ ^{12}\mathrm{C}, \overset{(-)}{\nu}_\ell\ ^{12}\mathrm{C}^*$ ($\ell = e, \mu, \tau$), whose signature is the monochromatic photon from carbon de-excitation ($E_\gamma = 15.1$ MeV), above $\mathcal{E}_h$.
(5) $\overset{(-)}{\nu}_\ell\ e^-, \overset{(-)}{\nu}_\ell\ e^-$, which yields a single signal, above $\mathcal{E}_h$, due to the recoil electron.

3. Neutrino mixing: events in LVD

In the study of supernova neutrinos, ν_μ and ν_τ are indistinguishable, both in the star and in the detector; consequently, in the frame of three-flavor oscillations, the relevant parameters are just $(\Delta m^2_{\rm sol}, U^2_{e2})$ and $(\Delta m^2_{\rm atm}, U^2_{e3})$. We will adopt the following numerical values: $\Delta m^2_{\rm sol} = 5 \cdot 10^{-5}\mathrm{eV}^2$, $\Delta m^2_{\rm atm} = 2.5 \cdot 10^{-3}\mathrm{eV}^2$, $U^2_{e2} = 0.33$; the selected solar parameters $(\Delta m^2_{\rm sol}, U^2_{e2})$ describe a LMA solution, favored by recent analyses [9].

For a normal mass hierarchy scheme, neutrinos (not anti-neutrinos) cross two resonance layers: one at higher density (H), which corresponds to $\Delta m^2_{\rm atm}$, and the other at lower density (L), corresponding to $\Delta m^2_{\rm sol}$.[1] Given the energy range of supernova neutrinos (5 MeV $\lesssim E_\nu \lesssim$ 50 MeV), and considering a star density profile $\rho \propto 1/r^3$, the adiabaticity condition is always satisfied at the L resonance for any LMA solution, while at the H resonance, this depends on the value of U^2_{e3}. When $U^2_{e3} \gtrsim 5 \cdot 10^{-4}$ the conversion is completely adiabatic, meaning that ν_e are completely converted into the mass eigenstate ν_3 (detected at the Earth mainly as ν_μ and ν_τ). Therefore, the SN neutrino signal could feel the effect of U^2_{e3} (and could also help to discriminate the type of mass hierarchy) [10], [11], [12].

We calculated the number of events expected in the reaction channels *(1)-(4)* in LVD,[2] in the cases of no-oscillation and oscillation, under the following hypotheses:

⋆ We assumed a supernova exploding at $D = 10$ kpc, with an energy release $E_{\rm tot} = 3 \cdot 10^{53}$ erg, pure Fermi-Dirac time integrated spectrum, energy equipartition, and neutrinospheres temperatures as $T_{\nu_e} = T_{\bar\nu_e} = T_{\nu_x}/2$.

⋆ We included the active mass of the detector and the energy thresholds, as described in Sect.2. We used the following values of detection efficiencies above threshold: $\epsilon_{\bar\nu_e\, p, e^+ n} = 95\%$ and $\epsilon_{n\, p, d\, \gamma_{2.2}} = 50\%$; $\epsilon_{\nu_e\, \mathrm{C,N}\, e^-} = 85\%$; $\epsilon_{\bar\nu_e\, \mathrm{C,B}\, e^+} = 70\%$; $\epsilon_{\nu_\ell\, \mathrm{C}, \nu_\ell\, \mathrm{C}} = 55\%$ [13].

⋆ In the oscillation case, we used two extreme values for U^2_{e3}: $U^2_{e3} = 10^{-2}$ and $U^2_{e3} = 10^{-6}$, and the above mentioned mixing parameters (normal mass hierarchy, LMA solution).

[1] For inverted mass hierarchy, transitions at the higher density layer occur in the anti-neutrino sector, while at the lower density layer they occur in the neutrino sector. Anyway, both in case of normal and inverted mass hierarchy, the dynamics of collapse is not affected, since these layers are located far outside the core of the star.

[2] The signature of channel *(5)* is not as clear as the other ones, and the number of expected events is low; therefore, we disregard it in the following.

$\star$ We did not include Earth matter effects ("open sky" neutrino burst).

Fig.1 shows the number of expected events ver-

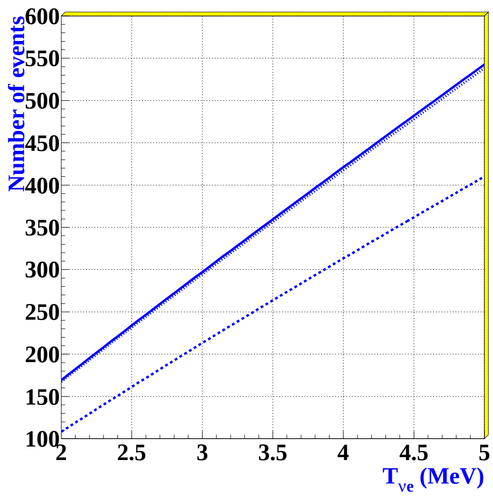

Figure 1. Number of events expected in LVD, in the reaction $\bar{\nu}_e p, ne^+$, as a function of $T_{\bar{\nu}_e} \equiv T_{\nu_e}$: the dashed line represents the no-oscillation case, while full and dotted lines represent the oscillation case, adiabatic and non adiabatic, respectively.

sus T_{ν_e} in the inverse β decay $\bar{\nu}_e$ reaction: a large increase due to ν mixing is clearly visible, with respect to the no-oscillation case. It should be noted that the number of $\bar{\nu}_e p$ events is practically the same both for adiabatic and non-adiabatic conditions, since, for normal mass hierarchy, MSW effect takes place in the neutrino sector only. Quite a different picture would appear, if we were to assume inverse mass hierarchy.

Fig.2 shows the expected total number of c.c. interactions with ^{12}C, due to both ν_e and $\bar{\nu}_e$.[3] The mixing results in an increase of the number of events, either for adiabatic or for non adiabatic conditions: in case of adiabaticity the increase is larger, and this is solely due to ν_e interactions.

Finally, the expected number of events in neutral currents (n.c.) interactions with ^{12}C is shown in Fig.3: they are of course insensitive to ν

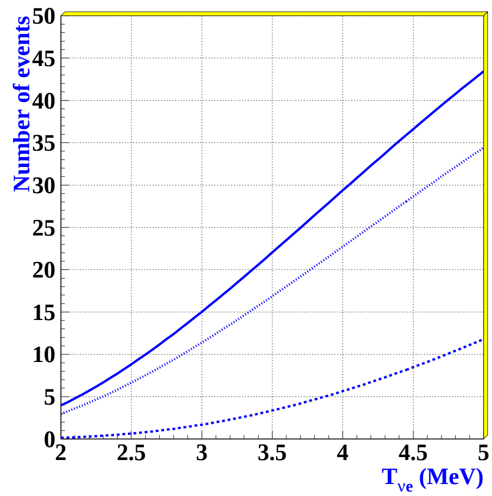

Figure 2. Number of events expected in LVD, in c.c. interactions with ^{12}C as a function of $T_{\bar{\nu}_e} \equiv T_{\nu_e}$: the dashed line represents the no-oscillation case, while full and dotted lines represent the oscillation case, adiabatic and non adiabatic, respectively.

mixing. However, the number of carbon de-excitations can test the temperature of neutrinospheres at the source [14], and therefore could be used in combination with c.c. data to overcome theoretical uncertainties on the temperature.

4. Conclusions and discussion

The observation of a neutrino burst due to the explosion of a galactic supernova can add precious information about neutrino mass and mixing scenarios, in a complementary way with respect to solar, atmospheric and terrestrial ν experiments.

We have studied the signal at LVD from a SN exploding at $D = 10$ kpc for 3-flavor ν oscillation, assuming the LMA-MSW solution for solar ν and normal mass hierarchy. We calculated the expected number of events for extreme values of U_{e3}^2. Varying oscillation parameters, we found an increase up to 50% of the signal due to inverse β decay, and an increase by almost one order of magnitude of the signal due to c.c. reactions on carbon. We remind the reader that the signatures of these reactions in LVD are very clear.

We plan to extend the calculation to include

[3] Since mean life times of $\beta^{\pm}$ decay are similar (see Sect.2), ν_e and $\bar{\nu}_e$ are distinguishable only on statistical basis. Note that, at $T = 4$ MeV, we expect 6 events due to $\bar{\nu}_e\,^{12}$C,^{12}B e^+ in both cases with oscillations.

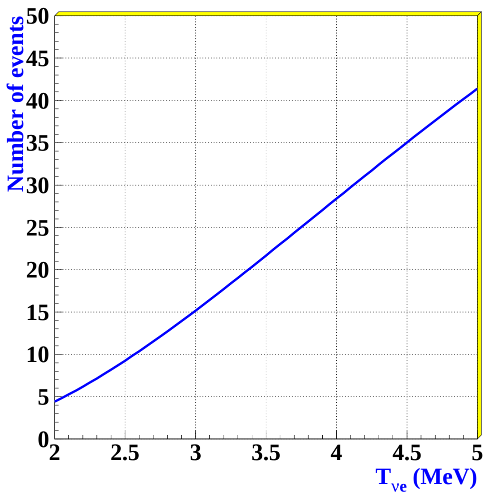

Figure 3. Number of events expected in LVD, in n.c. interactions with ^{12}C as a function of T_{ν_e}.

more refined energy and time distributions of ν and the Earth matter effect. The latter leads to peculiar distortions of the spectra of SN $\bar{\nu}_e$ and ν_e, depending on their trajectory in the Earth,[4] on mass hierarchy and on adiabaticity of H resonance. Earth matter effect amplifies the difference between the two cases with oscillation in Fig.2, due to ν_e regeneration in the non-adiabatic case.

The combination of well separated classes of events, namely those due to charged and neutral current interactions on carbon and those due to inverse β decay, can help to distinguish between different scenarios of massive neutrinos and astrophysical parameters. In addition, as recently discussed [15], the comparison of the results of a *network* of detectors could permit us to fully exploit the supernova neutrino signal, thus learning on neutrino intrinsic properties. Indeed, we could finally confirm the solution of the solar neutrino problem, learn on the mixing U_{e3}, and identify the hierarchy of the neutrino mass spectrum.

[4]Even if we should not detect the optical counterpart of the next galactic supernova, the ν signal itself can inform us on the source position by the directional (anti)neutrino electron scattering as observed by Čerenkov detectors.

5. Acknowledgements

This work was initiated by a conversation with Sandro Bettini, to whom we are grateful.
We would like to acknowledge the Gran Sasso Laboratory Staff for the continuous and valuable support.

REFERENCES

1. A.Burrows, D.Klein and R.Gandhi, Phys. Rev. **D45** (1992) 3361.
2. H.T.Janka and E.Müller, A&A **306** (1996) 167.
3. A.Mezzacappa et al., Phys. Rev. Lett. **86** (2001) 1935.
4. G.G.Raffelt, astro-ph/0105250.
5. K.Takahashi, M.Watanabe, K.Sato and T.Totani, Phys. Rev. **D64** (2001) 093004.
6. S.P.Mikheev and A.Y.Smirnov, Sov. Phys. JETP **64** (1986) 4.
7. L.Wolfenstein, Phys. Rev. **D17** (1978) 2369.
8. M.Aglietta et al., Il Nuovo Cimento A105 (1992) 1793.
9. G.L.Fogli et al., hep-ph/0106247.
10. T.K.Kuo and J.Pantaleone, Rev. Mod. Phys. 61 (1989) 937, and refs. therein.
11. G.Dutta, D.Indumathi, M.V.Murthy and G.Rajasekaran, Phys. Rev. D **61** (2000) 013009.
12. A.S.Dighe and A.Yu.Smirnov, Phys. Rev. D62, (2000) 033007.
13. P.Antonioli et al., NIM **A 309** (1991) 569.
14. W.Fulgione, Nucl. Phys.**B77** (1999) 435.
15. C.Lunardini and A.Yu.Smirnov, hep-ph/0106149